Next-Generation Heavy-Duty Powertrains

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ACE133 Overview: Next-Generation HD Powertrains

New projects addressing R&D challenges in achieving the MD/HD engine system efficiency goals
4 tasks reviewed together in FY 19

Timeline

- **FY 19-21** AOP Lab Call project plan: AOI 1B: Heavy/Medium Duty Combustion Research
- *Details for plan in Lab Call response*

Barriers**

- Improved understanding of the combustion processes to increase engine efficiency and reduce engine-out emissions
- Identify and address fundamental barriers to commercialization of LTC into MD/HD vehicles
- Challenges of cold-start and restart for electrification of MD/HD powertrains

Budget

Task	FY19
Task1: Advanced diagnostics + Cummins CRADA	$300K
Task 2: Neutron imaging for MD/HD	$200K
Task 3: Next generation MD/HD LTC	$250K
Task 4: Cold-start/restart for electrification of MD/HD engines	$300K

Partners / Interactions

- Regular status reports to DOE
- Industry technical teams, DOE working groups, and one-on-one interactions
- Industry: Cummins CRADA, BorgWarner
- Engine Combustion Network (ECN)
- Universities: U. Wisconsin, U. of Central Florida
- DOE Labs: SNL, ANL
- VTO: Other ACE projects, Fuel Tech./Co-Optima
- Support to DOE VTO, Strong links to 21CTP, Advanced Engine Crosscut, AEC MOU, IEA Combustion Task

* Vehicle Technologies Office AOP Lab Call, April 13, 2018

Relevance and Project Objectives

Overall objective across the four projects

Advance the foundational knowledge base for the next generation of MD/HD engine systems to increase engine efficiency and reduce engine-out emissions

Foundational Medium-Duty/Heavy-Duty Combustion Research

Fundamental understanding needed to improve predictive models and future engine design

- Task 1: Advanced diagnostics for MD/HD engine systems, including Cummins CRADA

Develop fundamental data sets using x-ray and neutron diagnostics

- Task 2: Neutron imaging of MD/HD engine system components

Removing Barriers for MD/HD Low-Temperature Combustion

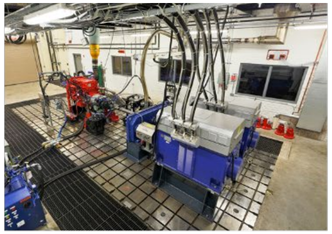
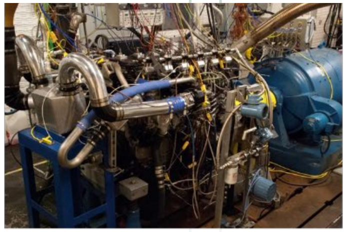
Technical barriers for achieving high-load operation and addressing low stability

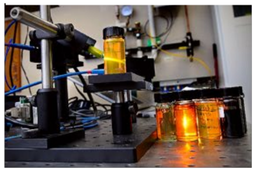
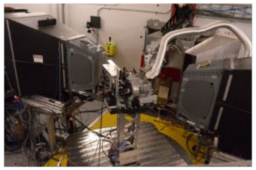
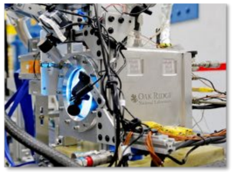
- Task 3: Next generation LTC engines for MD/HD vehicles for efficient, stable, and full-load operation

Advancing Medium-Duty/Heavy-Duty Electrification

Lack of understanding of cold-start and restart emissions for partially electrified MD/HD truck applications

- Task 4: Challenges of cold-start and restart for electrification of MD/HD powertrains


Milestones for FY 19 and FY 20

All milestones met or are currently on track to be met on time

Month/Year	Description of Milestone	Status
Dec. 2018	Identify and characterize hybrid architectures and engine combinations under investigation for heavy-load restarts. (Task 4 – MD/HD Cold-Start/ Restart)	Met
March 2019	Complete review of candidate temperature measurement techniques suitable for real-world MD/HD engines. (Task 1 – Advanced Diagnostics)	Met
June 2019	Complete investigation on multi-cylinder engine platform for medium/high-load operation barriers and complete low- load stability investigations. (Task 3 – HD LTC)	On Track
Sept. 2019	Complete data set of transient operation evaluation of the HD engine and identify specific operation modes to address with engine combustion improvements. (Task 4 - MD/HD Cold-Start/ Restart)	On Track
Dec. 2019	Provide design for in-cylinder diagnostic validation with neutron diagnostics. [Task 1 – Advanced Diagnostics]	On Track
March 2020	Complete and submit annual reports for the entire DOE Advanced Combustion Systems R&D program across all funded laboratories. [Program Management]	On Track
June 2020	Complete Preliminary neutron imaging campaign of an MD/HD fuel injector [Task 2]	On Track
Sept. 2020	Complete characterization of deterministic features of cyclic instability at lower loads. Characterize control authority with LTC on a single-cylinder engine platform. [Task 3]	On Track

Time	Go/No-go Decision Description	Task
FY19/Q4 (12 months)	Criteria: Demonstrate proposed temperature diagnostic from down-selected diagnostics. Go Path Action: Continue development leading to new high-fidelity data sets. No-go Path Action: Select alternative path for diagnostic.	Task 1 – Advanced Diagnostics

Overall Technical Approach:

4 tasks that work to achieve the overall objectives

Advance the foundational knowledge base for the next generation of MD/HD engine systems to increase engine efficiency and reduce engine-out emissions

Foundational Medium-Duty/Heavy-Duty Combustion Research

- **Task 1: Advanced diagnostics for MD/HD engine systems, including Cummins CRADA**
  - New **diagnostics** for measuring in-cylinder temperature and heat losses in metal engines during operation
- **Task 2: Neutron imaging of MD/HD engine system components**
  - Nondestructive **neutron imaging** diagnostic for insights into fuel injector dynamics in production-viable MD/HD fuel injectors

Removing Barriers for MD/HD Low-Temperature Combustion

- **Task 3: Next generation LTC engines for MD/HD vehicles for efficient, stable, and full-load operation**
  - MD/HD **metal engine experiments** along with thermodynamic analysis & CFD

Advancing Medium-Duty/Heavy-Duty Electrification

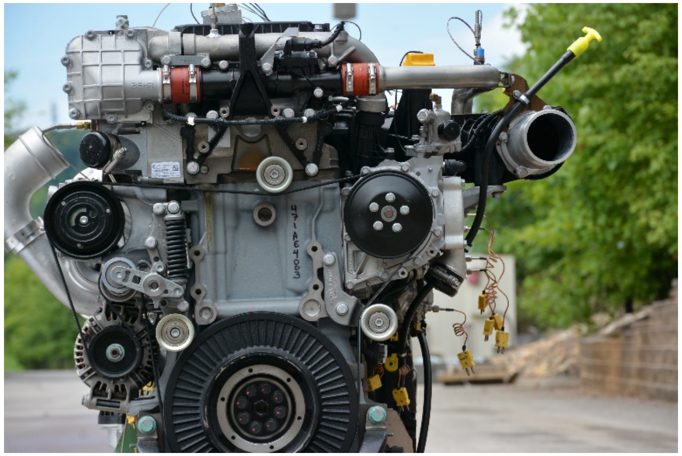
- **Task 4: Challenges of cold-start and restart for electrification of MD/HD powertrains**
  - **Engine experiments** in advanced **HIL** laboratories with **unique emissions characterization**

Additional details for task specific approaches including in progress/accomplishments

Technical Accomplishments and Progress

Along with task specific approach details

- Task 1: Advanced diagnostics including Cummins CRADA
  [Slides 7-10]
- Task 2: Neutron imaging of MD/HD engine system components
  [Slides 11-14]
- Task 3: Next generation LTC engines for MD/HD vehicles
  [Slide 15-16]
- Task 4: Challenges of cold-start and restart for electrification of MD/HD powertrains
  [Slide 17-19]



Barriers Addressed

1. Improved understanding of the combustion processes to increase engine efficiency and reduce engine-out emissions
2. Identify and address fundamental barriers to commercialization of LTC into MD/HD vehicles
3. Challenges of cold-start and restart for electrification of MD/HD powertrains

Accomplishments and Progress

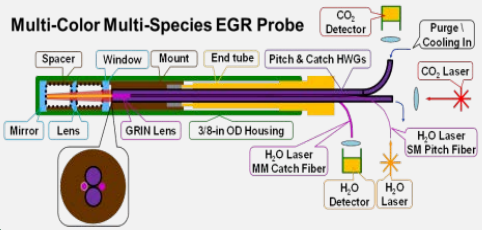
Task 1: Advanced diagnostics including Cummins CRADA

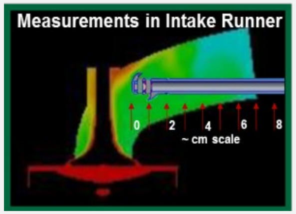
End-of-Project Goal: Establish **new diagnostics** for improved data on in-cylinder **surface temperatures** that will be **suited for use in realistic engines**, **including in-field use** with industrial partners; apply data to tune, assess, and improve predictive models.

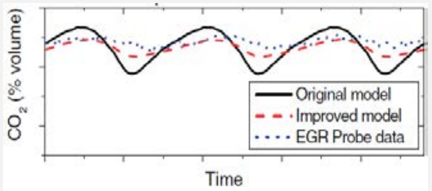
Improving Multi-Cylinder Engine Uniformity & Efficiency Through Novel Diagnostics

Focus on *Minimally Modified OEM Metal Engines*

– e.g., **EGR Probe** provides crank-angle-resolved CO_2, H_2O, Temperature & Pressure





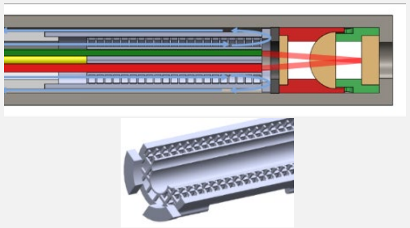


New project builds on previous experience and successful development of unique diagnostics suitable for use in production viable engines

Focus: In-cylinder temperature measurements

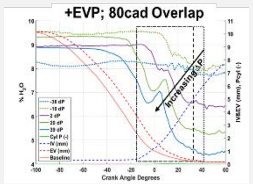
Diagnostic Improvements

High-Temp EGR Probe



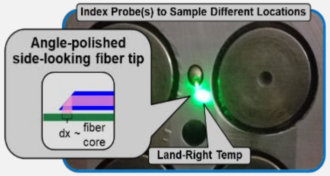
Diagnostic Applications

Improved Cylinder Scavenging



New Measurements

In-Cylinder Surface Temperature



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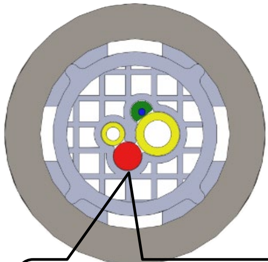
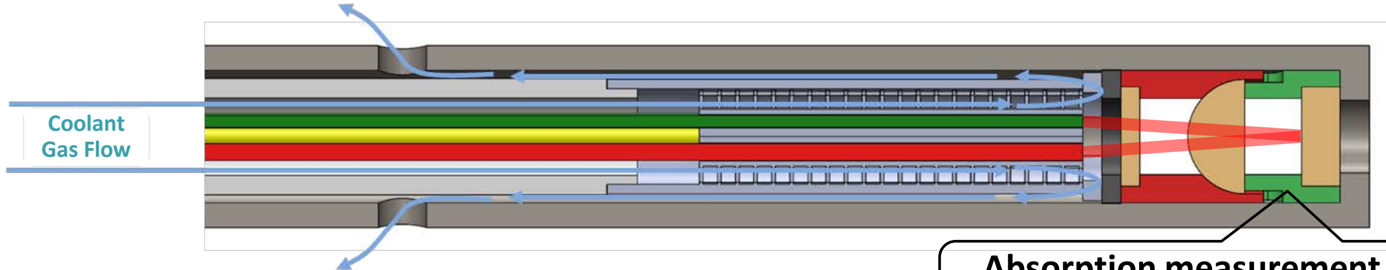
Spatiotemporally Resolved Exhaust Property Measurements

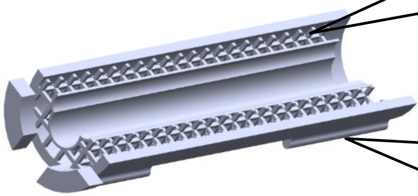
Collet positions
Pitch & Catch fibers





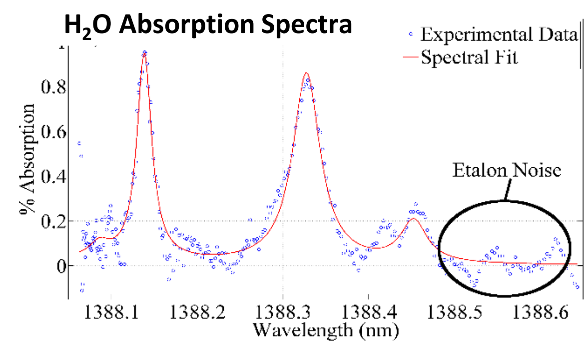
Absorption measurement occurs at probe tip

Optical Fibers
(Keep ≤ 250°C)

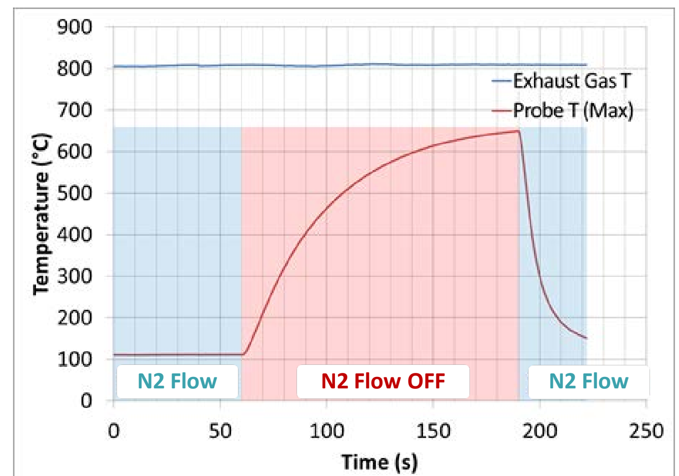


Internal Scaffold Structure
- Increases internal thermal resistance
- Allows for flow-through cooling

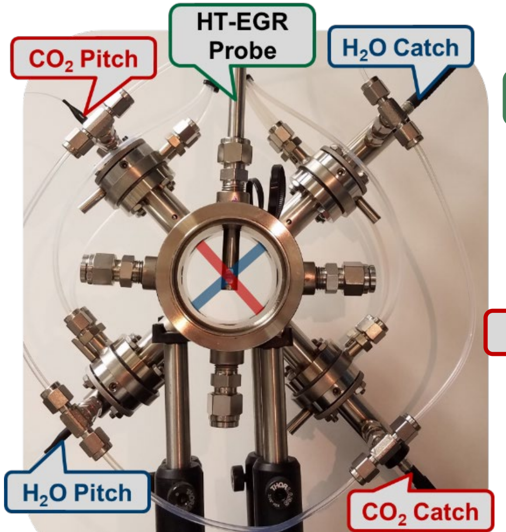
Broken Rib Standoffs
- Increases thermal resistance between collet and hot outer tube



- EGR Probe
  - 5kHz (1.2 CAD at 1000RPM) H_2O, CO_2, T & P
  - Based on absorption spectroscopy
  - Other species possible (e.g., CO, CH_4,..)
  - Many on-engine development applications in intake
- High-Temperature EGR Probe
  - Enables exhaust applications
  - Uses custom printed collet
  - Applicable to 800°C

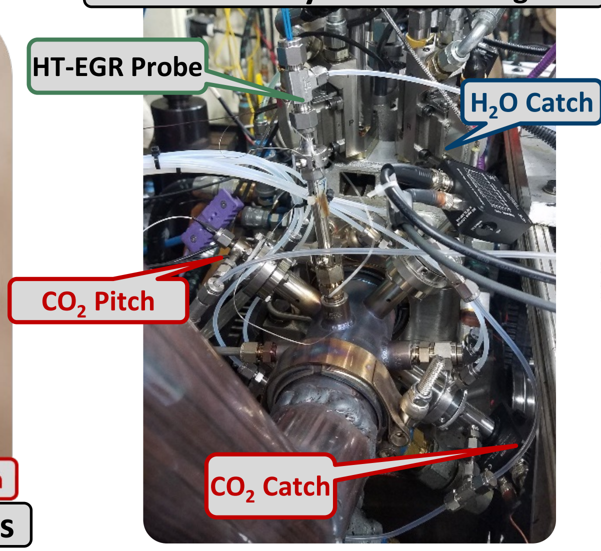


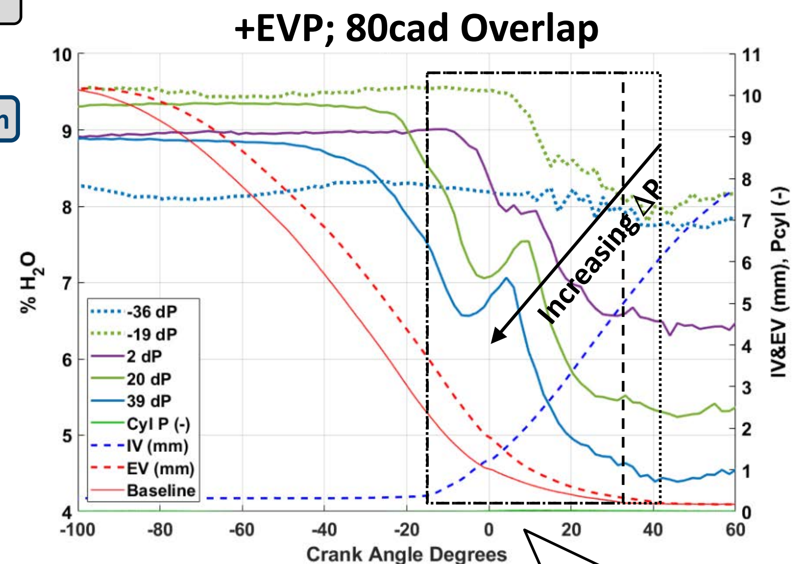
Measurements to Improve Cylinder Scavenging



Line-of-Sight & HT-EGR Probes

Cummins 1-Cylinder VVA Engine



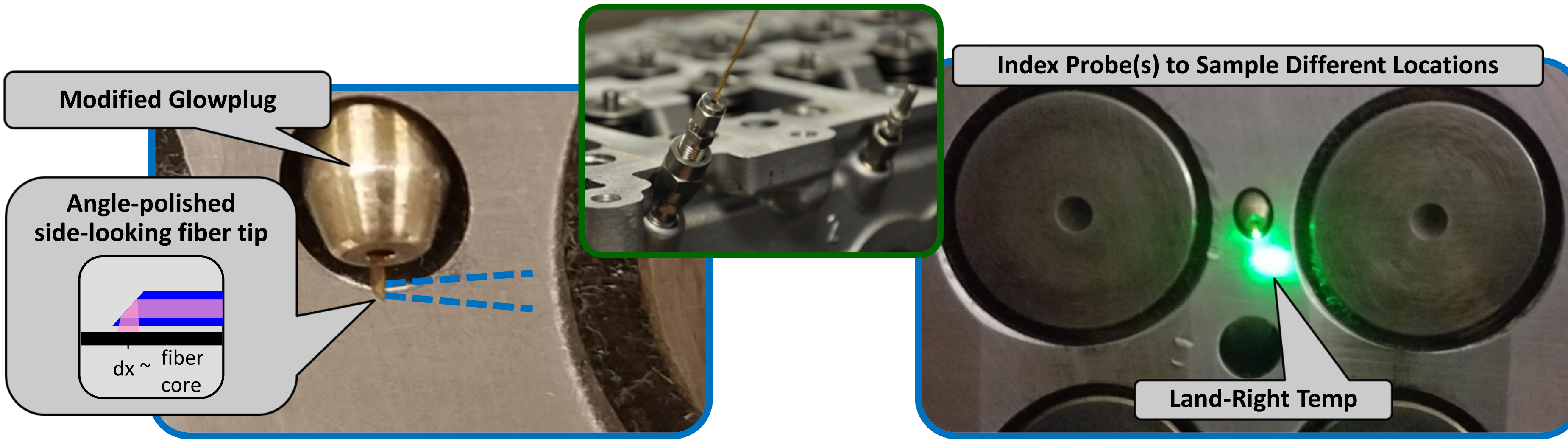


Valve Overlap for Baseline & +EVP

- Focus is enabling improved design
  - Intake/Exhaust flow geometry to improve scavenging
  - Measurement to validate & improve CFD
- Single-Cylinder Platform with VVA
  - Stoichiometric SI
  - Vary valve overlap, timing, number
- Exhaust %H_2O Well occurs at Intake Flow-Through
  - Simultaneous 5kHz measurements of CO_2, T & P
  - Well onset dynamic varies with operating conditions
  - ***Rich transient data for assessing CFD design tools***

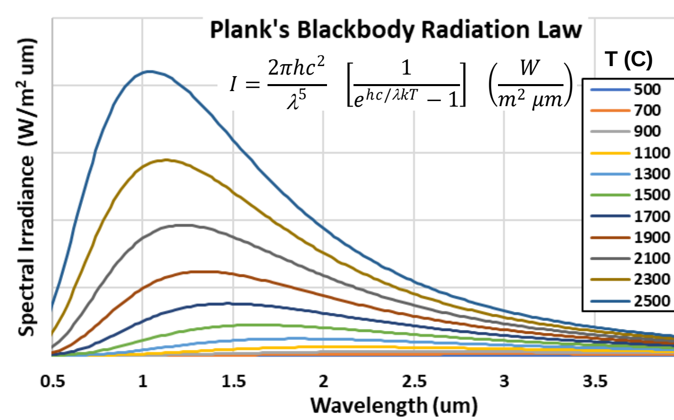
CRADA Campaign Teamwork at CTC

Real-Time On-Engine Cylinder Surface Temperature Candidates



- **Improved speed and accuracy of boundary conditions**
- **Specification**: crank-angle resolved, on-engine measurements
- **Approach: spectrally resolved pyrometry**
  - Established method – allows to focus on other diagnostic challenges
  - Plank's (blackbody radiation) Law, ca. 1900
- Many **Benefits**
  - No surface modifications (e.g., phosphor)
  - Little/No modifications required for optical-access
  - Robust and fast
  - Broad spectral potential (visible, NIR, MIR)
  - Potential to incorporate species measurements

Milestone met for candidate temperature measurement techniques

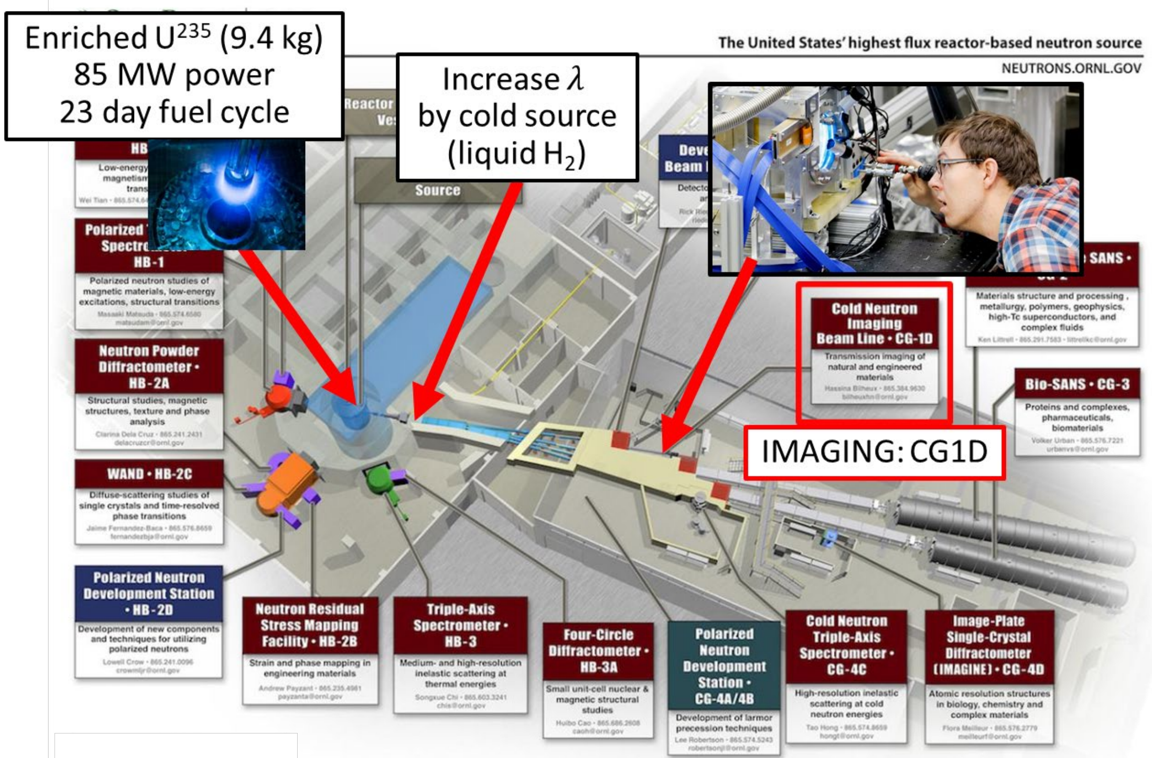


Accomplishments and Progress

Task 2 - Neutron imaging of MD/HD engine system components

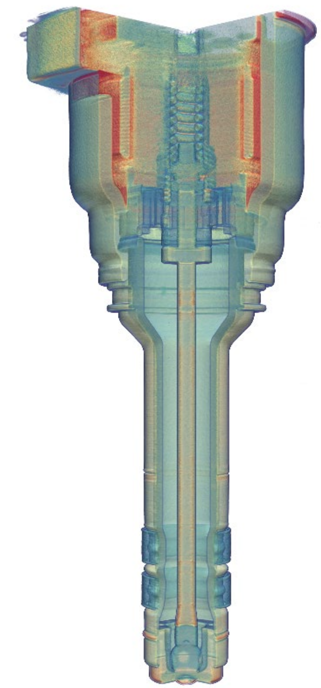
End-of-Project Goal: Provide **data sets** used for high-fidelity models from dynamic neutron imaging of production viable MD/HD fuel injectors [Back-up slide on why to use neutrons].

Neutron Imaging at ORNL's High Flux Isotope Reactor (HFIR)



HFIR is the United States highest flux reactor-based neutron source
Imaging at HFIR CG-1D Beamline: Hassina Bilheux Instrument Scientist

Neutron Computed Tomography (CT)



High-penetrating and **non-destructive technique** for obtaining finely resolved geometric information (50-100 µm) over a large field of view (7 x 7 cm)

Image from previous DOE work on GDI injector

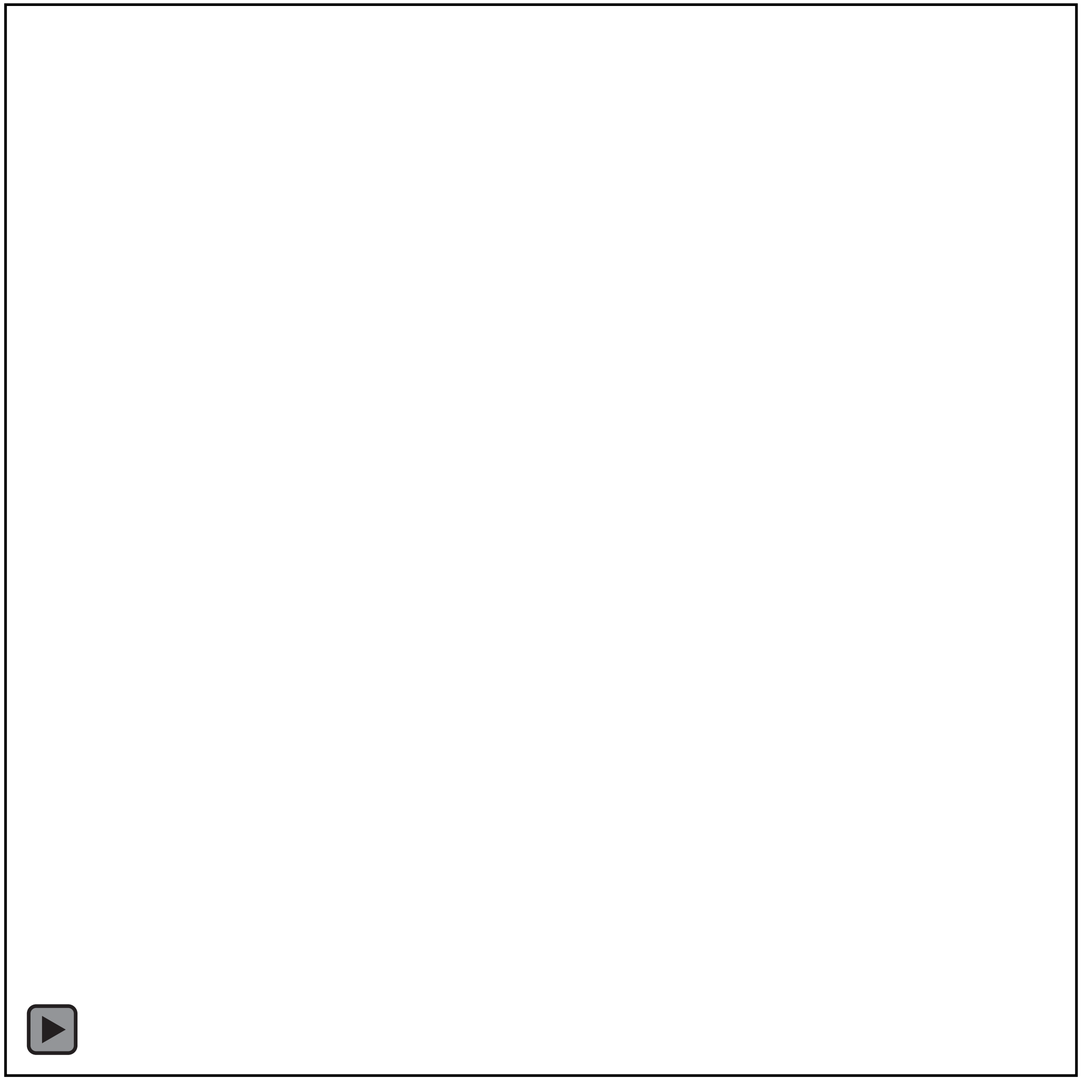
Recent Advancements in Neutron Imaging of Injectors Approach

Approach is similar to ongoing work with GDI injectors (Neutron Imaging of Advanced Transportation Technologies)

Dynamic Neutron Imaging
Visualize and quantify internal fluid and mechanical dynamics at small temporal and spatial scales (5 µs, 55 µm)

Movies at these timescales are a stroboscopic ensemble over millions of events

Dynamics that occur on the order of several seconds can be captured in real time



Images from previous work on GDI injector

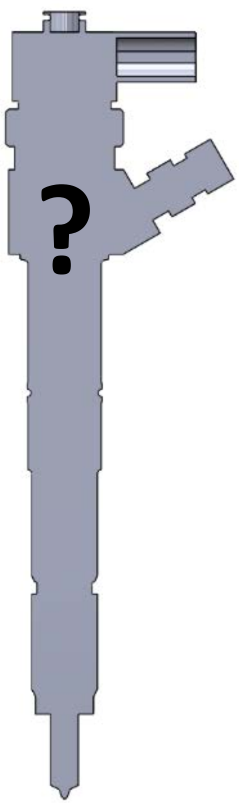
Planned activity for Year 1

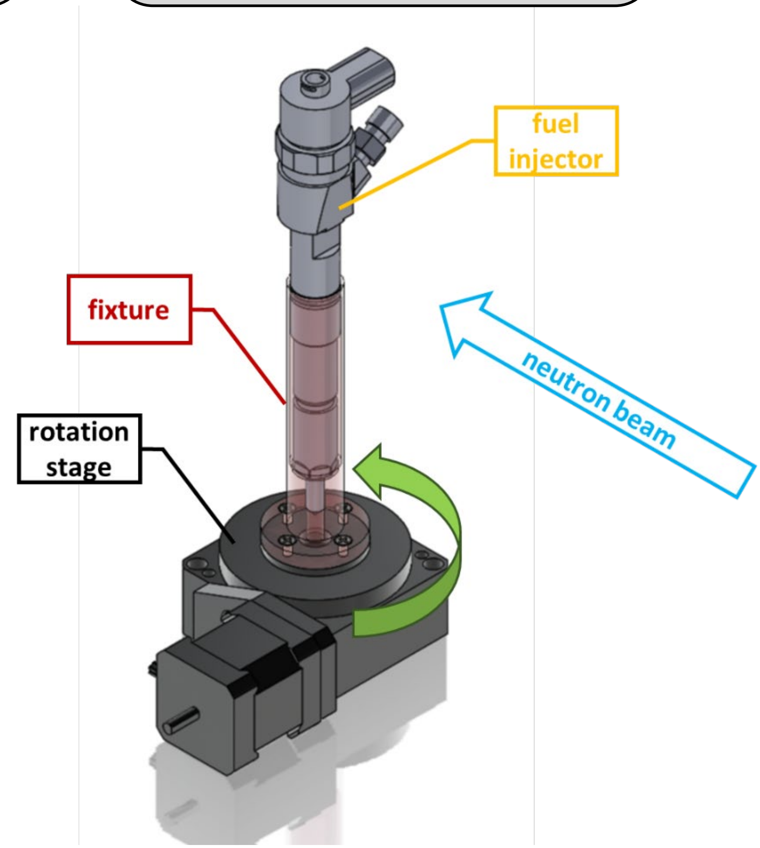
Tomography of common rail diesel injector

Internal geometry of hydraulic path in ECN injector is currently unknown

Damaged ECN injector provided by Sandia National Labs – L. Pickett

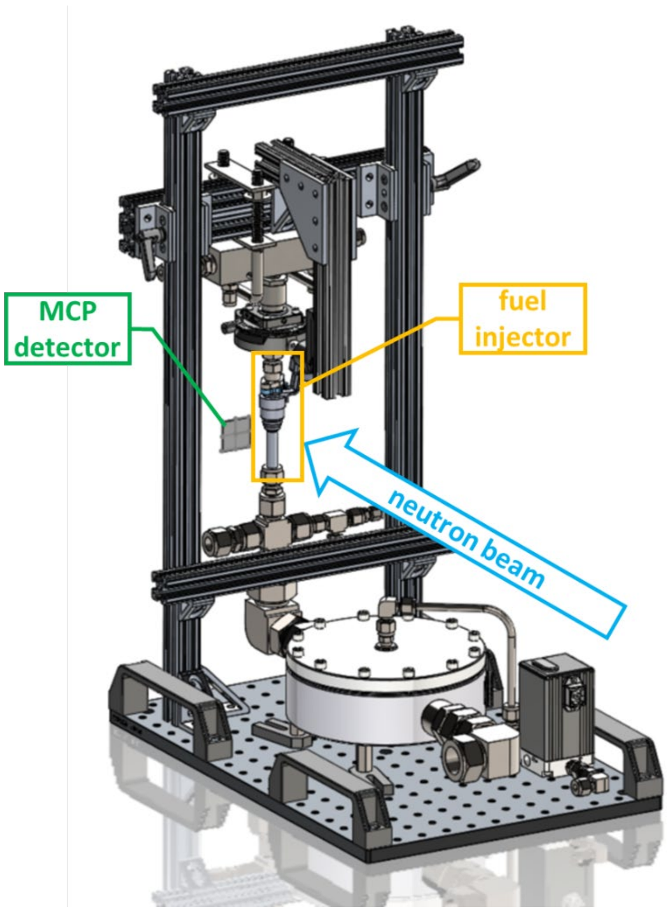
Perform neutron CT to obtain geometry supporting creation of 1D hydraulic model

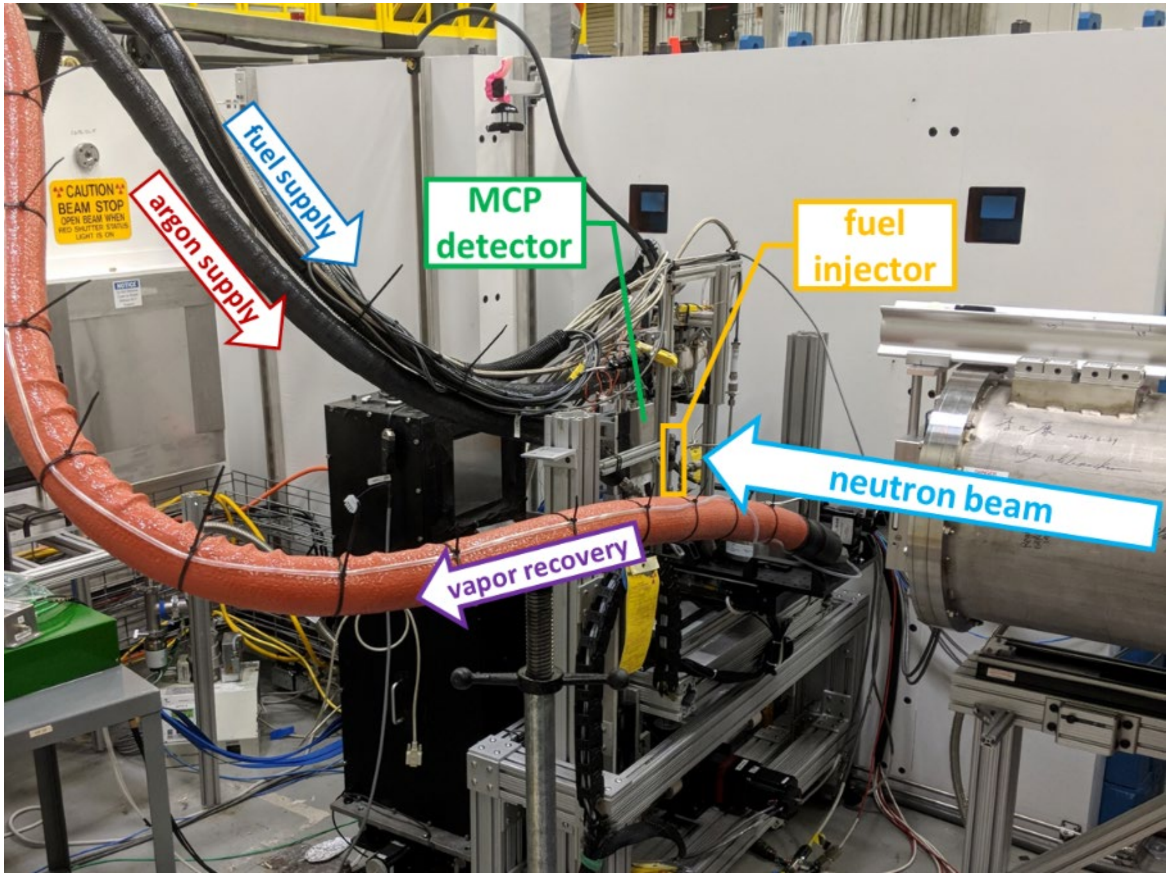




Planned activity for Year 1

Establish facility for dynamic neutron imaging of MD/HD injectors
Based on prior experience with imaging GDI injectors, work is underway in developing a spray rig to enable dynamic imaging of common rail injectors





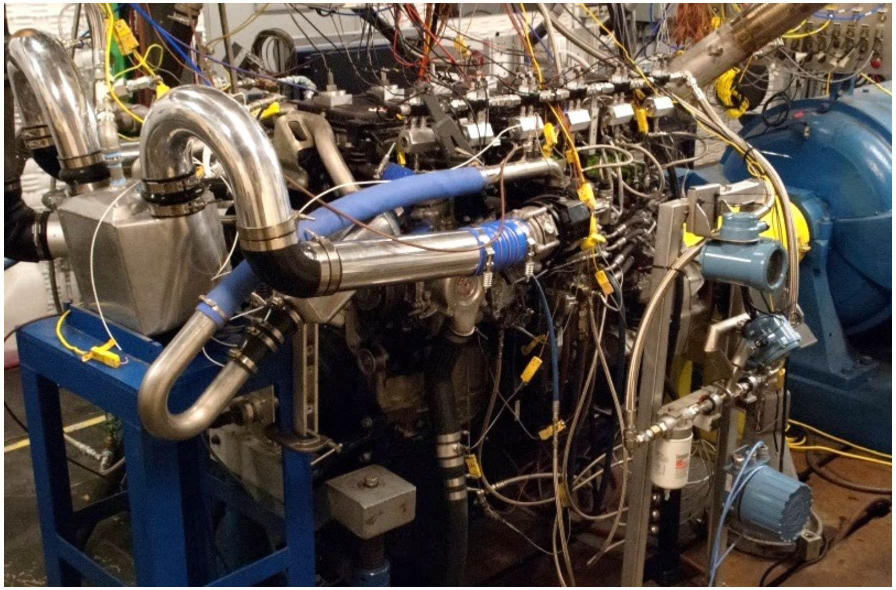
Images from previous work on GDI injector – Similar Approach for MD/HD injectors

Accomplishments and Progress

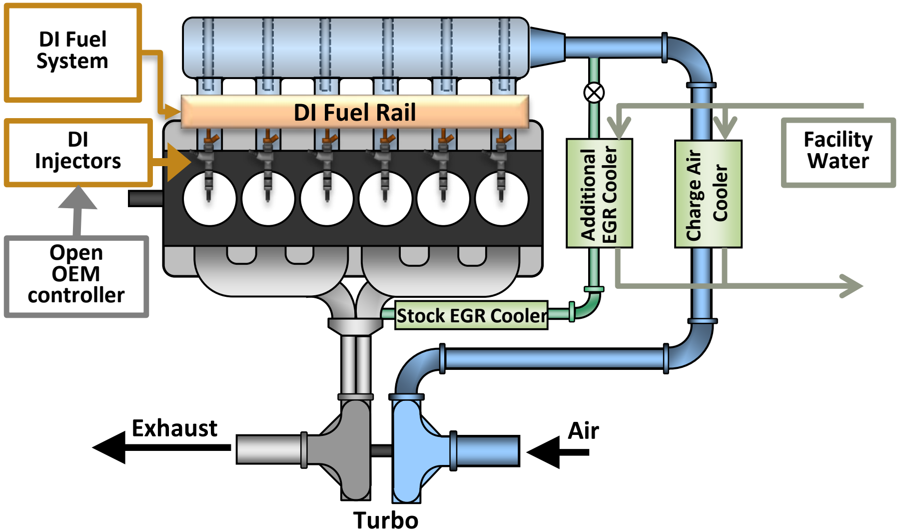
Task 3: Next generation LTC engines for MD/HD…

End-of-Project Goal: Experimentally demonstrate a pathway to improved engine efficiency and determine whether LTC might represent a pathway to mitigate/reduce the need to control nitrogen oxides (NOx) emissions to meet and exceed future emission targets.

Multi-Cylinder Engine Platform Year 1
Single-Cylinder Engine Platform Years 2-3

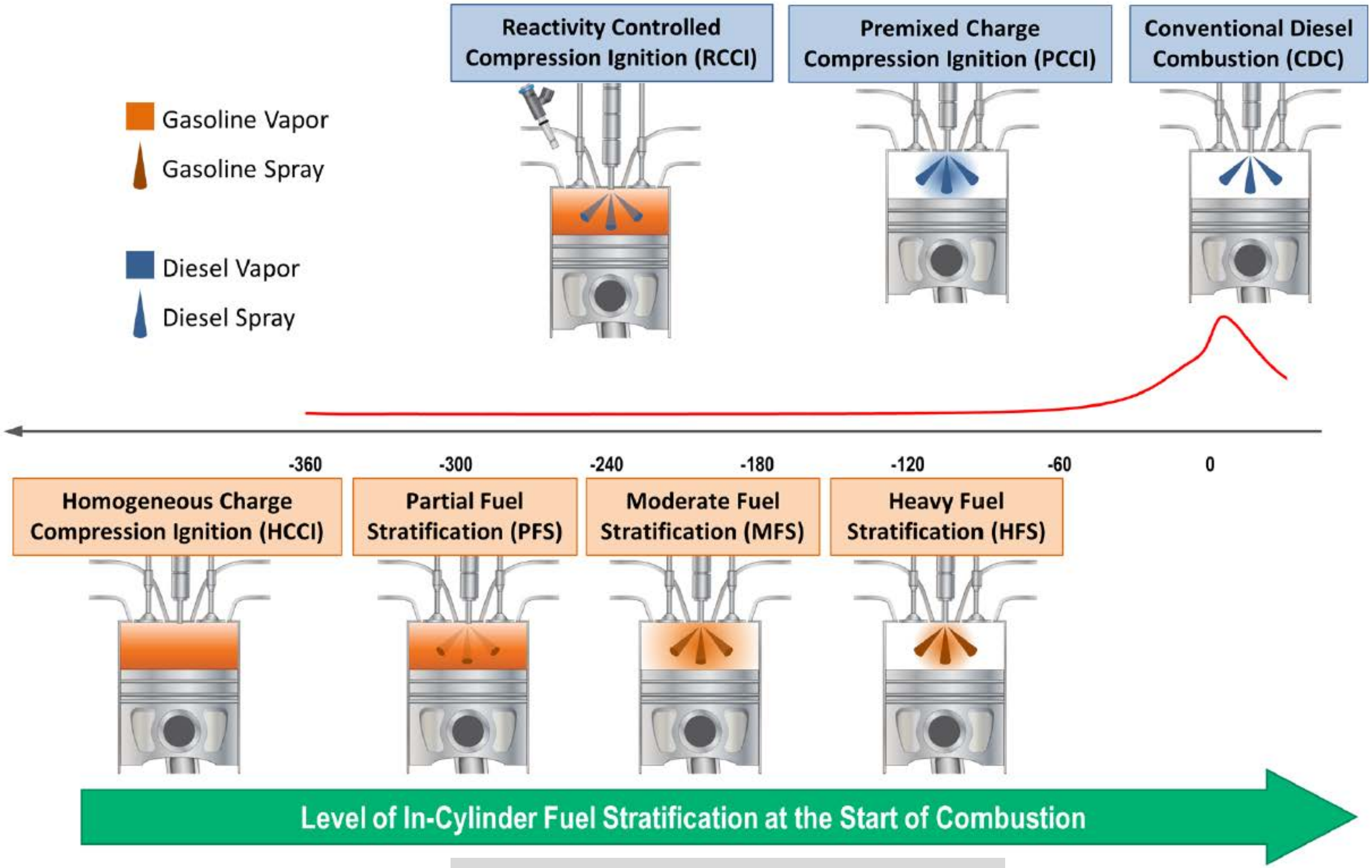


Multi-Cylinder DD15 platform at ORNL for use in initial stages of project



# Cyl	6 Cylinders
Disp	14.8L (2.47 L/cyl)
Bore	139mm
Stroke	163mm
CR	18.3:1

Categorizing the barriers to achieving medium- and high-load operation on a multi-cylinder metal engine over a range of promising LTC strategies



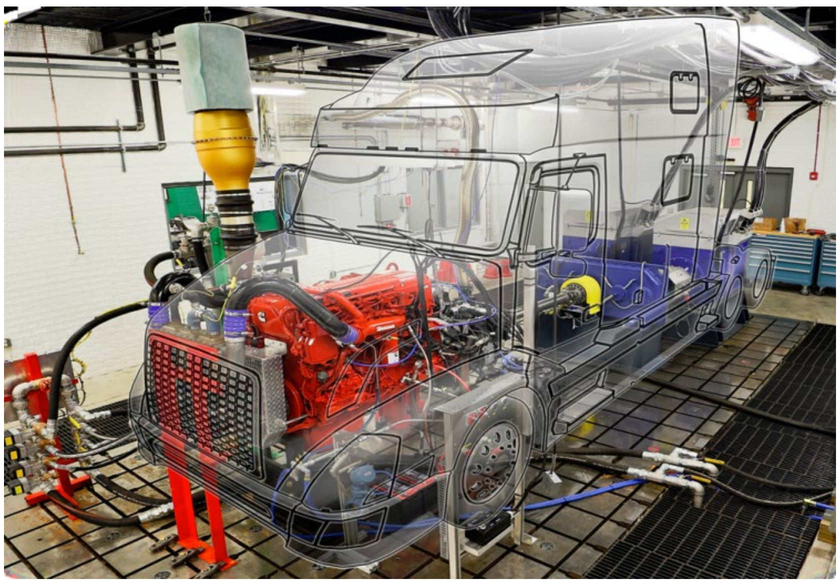
Engine Experiments Underway

Accomplishments and Progress

Task 4: Challenges of cold-start /restart for electrification of MD/HD powertrains

End-of-Project Goal: Provide vital combustion and emissions data sets from cold-start and restart scenarios with different hybrid truck architectures using advanced hardware-in-the-loop laboratory. Develop insights into fundamental barriers preventing improved fuel consumption in hybrid MD/HD trucks along with pathways to remove complexity.

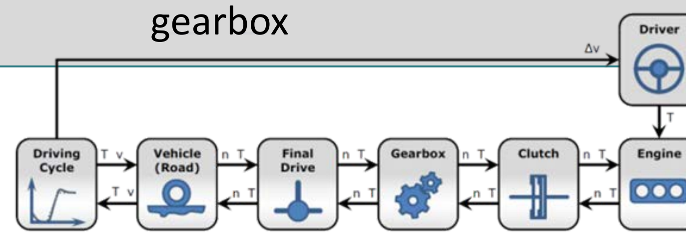
Hardware-in-the-loop engine experiments



Engine HIL Experiments Underway

Vehicle Systems Simulations

- **Vehicle simulation parameters are from a typical Class 8 line haul truck .**
  - Representative "highway" & "city" cycles *(backup slide for additional details)*
  - 15L Cummins ISX engine for all cases
  - Conventional trans.= 10 speed Eaton AMT
  - **Series unit** = 320 kW drive motor with a 320kW genset motor
  - **Parallel unit** = 320 kW pre-trans with 2-speed gearbox



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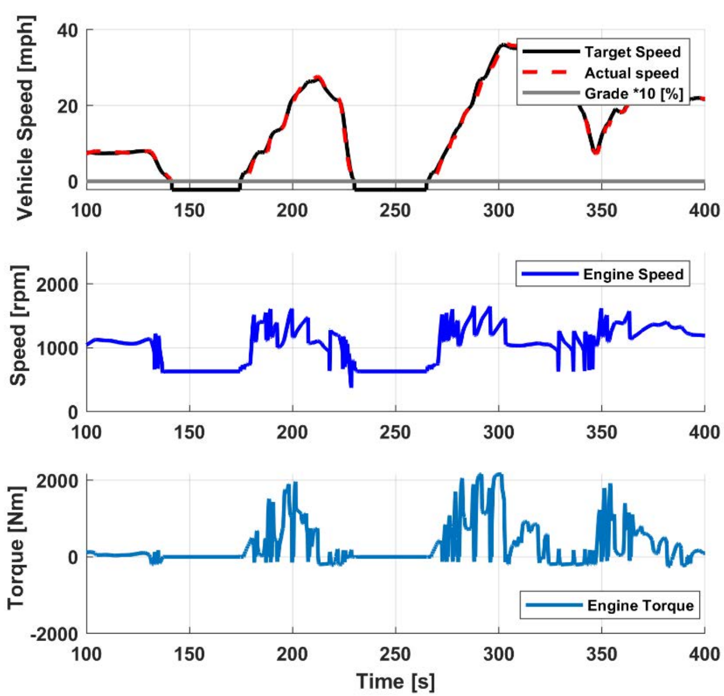
Milestone met: Identify and characterize hybrid architectures and engine combinations under investigation for heavy-load restarts

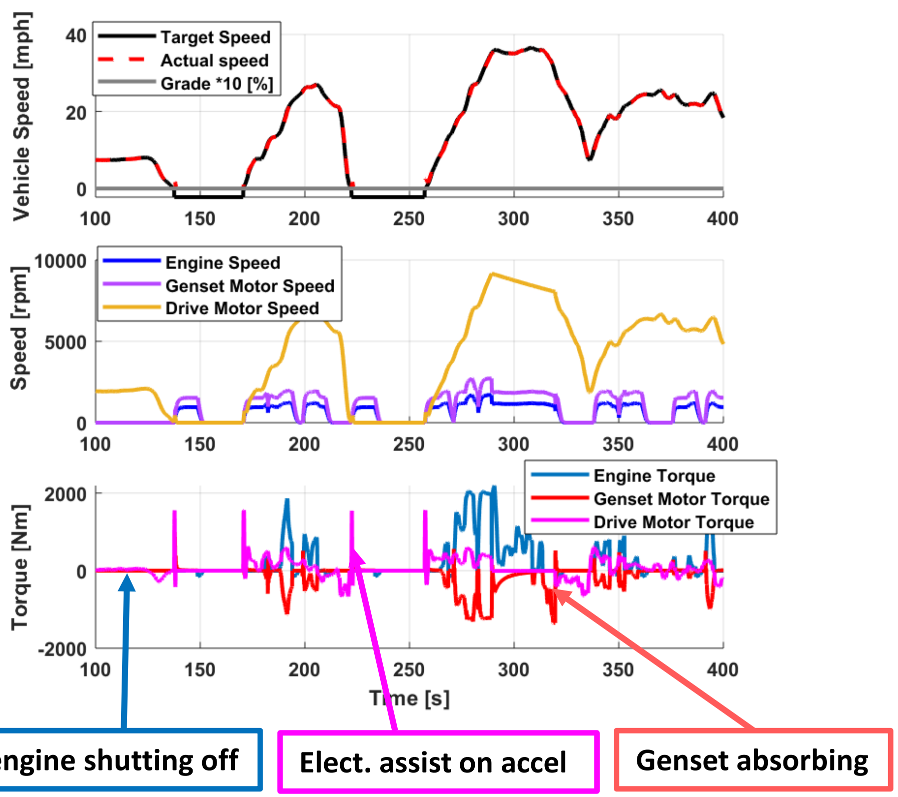
Results: ARB Cycle - Conventional vs Series

- **Series best suited for ARB cycle (city like)**

Conventional Powertrain



Series Hybrid



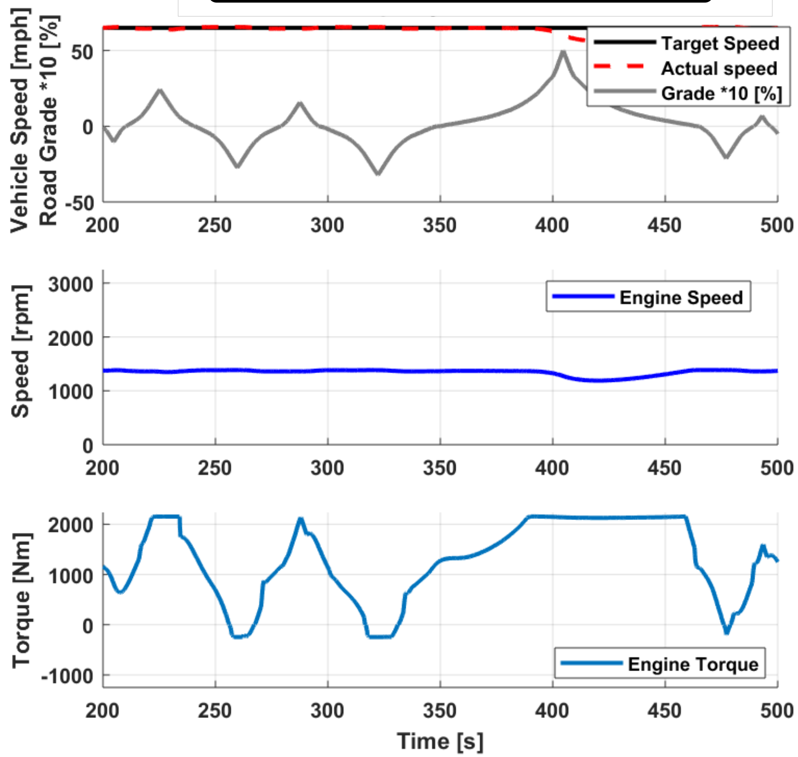
Series configuration on the ARB cycle the **engine is off for 47%** of the cycle

Milestone met: Identify and characterize hybrid architectures and engine combinations under investigation for heavy-load restarts

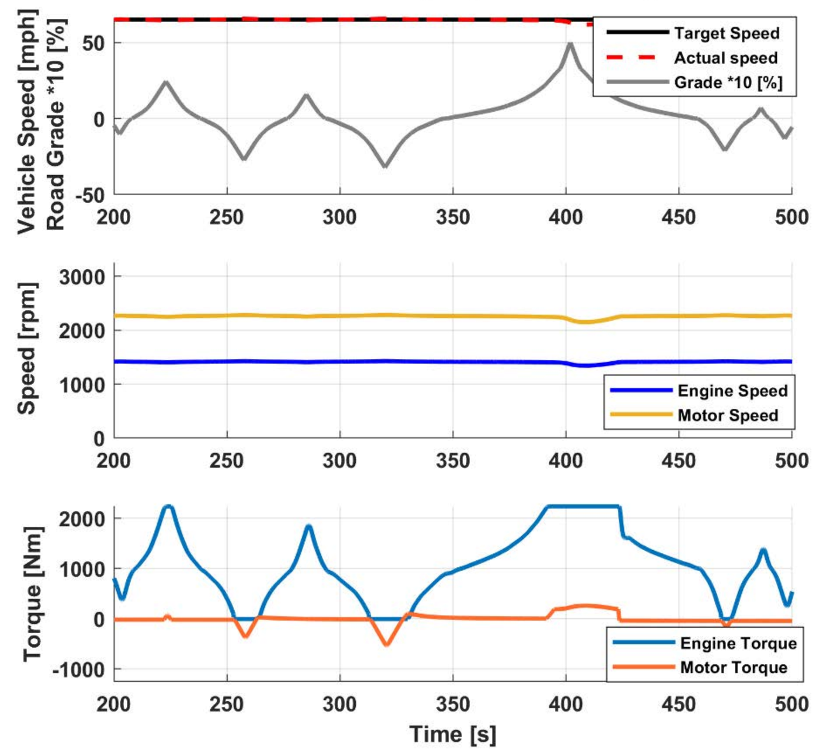
Results: 65 mph w/ grade cycle

- **Parallel better suited for highway cycles**

Conventional Powertrain



Parallel Hybrid



Milestone met using simulations: guided selection of hybrid architectures and move to MD platform

Reviewer Comments

New project – not previously reviewed

Collaboration and Coordination

Leveraging Collaborations:

- 21CTP, Advanced Engine Crosscut, IEA Combustion Task

15 Industry partners in the AEC MOU

- **Meet two times a year to share information with industry partners**
- **Other national labs and University partners as well**

Task Specific Collaborations

1: Advanced diagnostics + Cummins CRADA

- Cummins - Project Partner, Tim Lutz(CRADA Co-PI)
  - Joint measurement campaign at Cummins Technical Center
  - Measurements of cylinder scavenging to improve design models
  - February 5th to March 1st, 2019
- Cummins SuperTruck-II Project – Diagnostic applications, J. Dickson (Co-PI)
- Univ. of Central Florida – Applied diagnostics, S.S. Vasu
- *+ more in backup slide*

2: Neutron imaging MD/HD components

- ECN for coordination of injector work
- SNL – Lyle Pickett provided diesel injector for tomography
- ORNL Neutron Sciences – Hassina Bilheux instrument Scientist
- Office of Science programs
- Leveraging GDI imaging project techniques and analysis tools

3: Next generation MD/HD LTC engines

- Daimler Trucks – support for multi-cylinder engine experiments
- Cummins – support for single cylinder engine platform
- University of Wisconsin – CFD and SCE coord.
- ANL coordination for tasks
- SNL coordination for tasks
- Co-Optima – leveraging platforms
- CLEERS – data sharing

4. Cold-start and restart for elect. MD/HD

- Cummins support for project
- ORNL modeling and simulation team
- ORNL VSI laboratory team
- More collaborations in FY 20-21

Remaining Challenges and Barriers

Remaining challenges and barriers being addressed in three year plan

- **Foundational Medium-Duty/Heavy-Duty Combustion Research**
  - Improved predictive-model accuracy via better boundary condition data in realistic engines
- **Removing Barriers for MD/HD Low-Temperature Combustion**
  - Identify and address fundamental barriers to commercialization of LTC into MD/HD vehicles
- **Advancing Medium-Duty/Heavy-Duty Electrification**
  - Lack of understanding of the fundamental challenges of cold-start and restart for electrification of MD/HD powertrains

Proposed Future Work FY 19-21*

*Any proposed future work is subject to change based on funding levels.

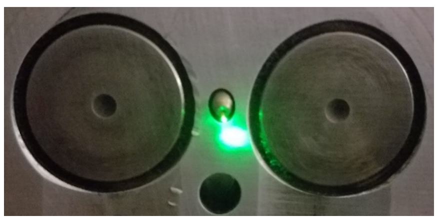
1: Advanced diagnostics + Cummins CRADA

FY19 - CFD analysis, tuning and assessment with scavenging measurements

- Cummins perform CFD analysis
- Present at SAE PF&L 2020

FY19 – Initial spatiotemporal surface-temperature (STST) diagnostic development

- Lab & engine develop./ shakedown at ORNL



FY 20 - 21

FY20 – Assess and refine STST diagnostic as necessary

- Assess impact of STST data on predictive models

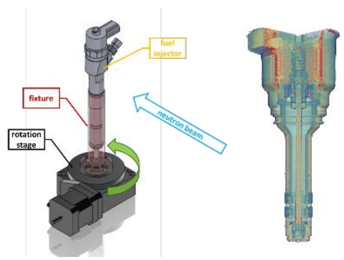
FY21 – Apply STST diagnostic to improve predictive models

- On-engine measurements for model calibration
- Quantify model improvements

2: Neutron imaging MD/HD components

FY 19: Development of sample environment for HD/MD fuel injection system

- Enabling neutron imaging specific to higher fuel pressures and a larger injector footprint *(building off previous GDI approach)*



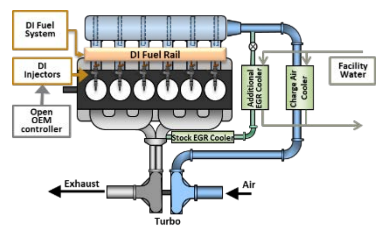
FY 20 - 21

- **FY 20**: Preliminary neutron imaging campaign of an MD/HD fuel injector.
- **FY 21**: Detailed information for MD/HD injector dynamics using refined diagnostics.

3: Next generation MD/HD LTC engines

FY19: Build data set over a range of LTC modes under investigation

- Using multi-cylinder engine platform for medium- and high-load operation barriers and complete low-load stability investigations.



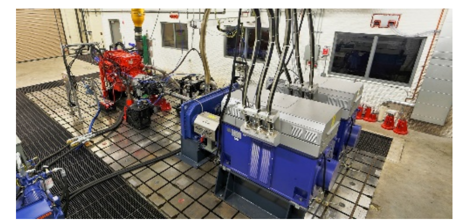
FY 20 - 21

- **FY20**: Control authority with LTC + deterministic features of cyclic instability on a single-cylinder engine platform.
- **FY21**: Characterize ability for new piston bowl and injector design to overcome barriers

4: Cold-start and restart for elect. MD/HD

FY19: Characterize the challenges and barriers of selected MD/HD hybrid architectures

- HIL experiments focused on restart characteristics related to emissions and noise, vibration and harshness (NVH).

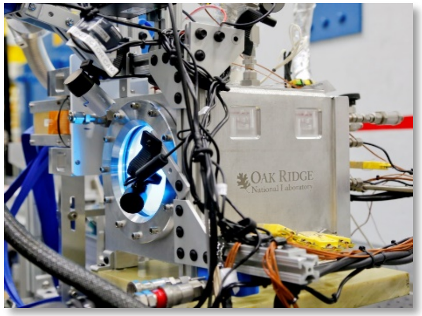


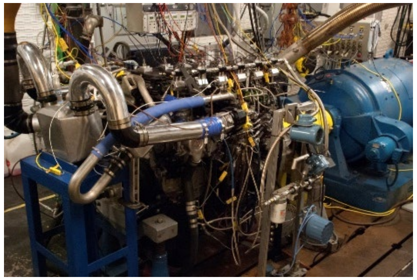
FY 20 - 21

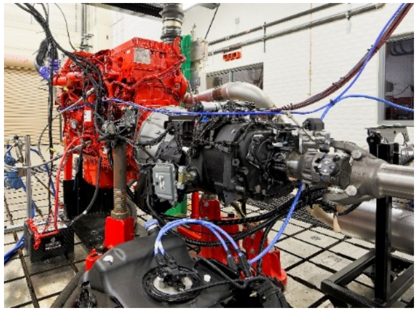
- **FY20**: Demonstrate the ability of selected mitigation pathways to reduce restart emissions and NVH.
- **FY21**: Determine the capability of reducing the content and complexity

ACE133 Summary

- Relevance
  - Advance the foundational knowledge base for the next generation of MD/HD engine systems to increase engine efficiency and reduce engine-out emissions
- Approach/Strategy
  - Task 1: Advanced diagnostics including Cummins CRADA
  - Task 2: Neutron imaging of MD/HD engine system components
  - Task 3: Next generation LTC engines for MD/HD vehicles
  - Task 4: Cold-start and restart for electrification of MD/HD powertrains
- Technical Accomplishments
  - Task 1: Milestone met for temp. diagnostics
  - Task 2: Build up of MD/HD injector neutron imaging
  - Task 3: Engine experiments underway, SCE platform underway
  - Task 4: Milestone met identifying hybrid architectures using simulation
- Collaboration and Coordination
  - Tech Teams, 21CTP, AEC, Adv. Engine CrossCut and National lab partners
  - Cummins CRADA, Daimler Trucks, ECN, Cummins U. Wisc
- Proposed future work
  - FY 19 -21 plan to advanced each of the 4 tasks





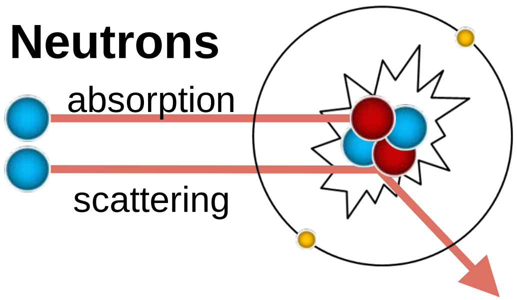


Technical Backup Slides

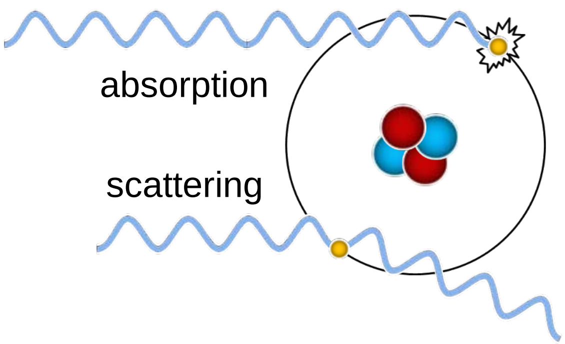
1. Why use neutrons as a diagnostic
2. Neutron Computed Tomography (CT) detail
3. Restart task HD drive cycle details
4. Adv. Diagnostics + Cummins CRADA collaboration details
5. HD HIL Laboratory (VSI Lab) details

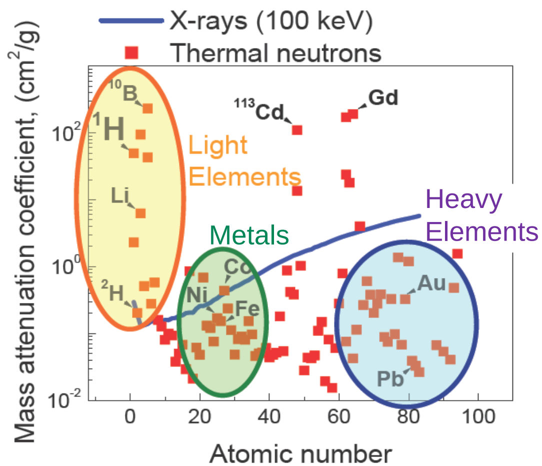
Approach: Why neutrons?

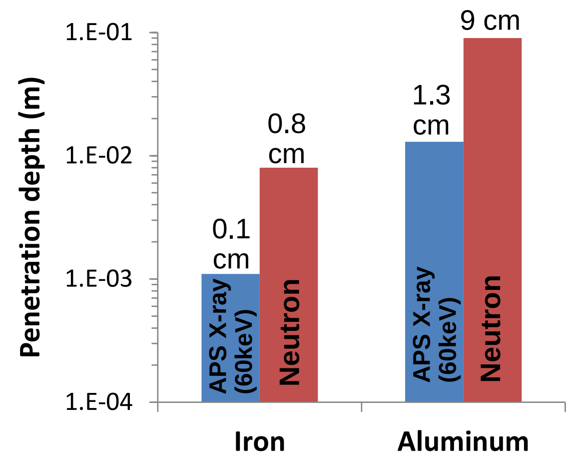
Neutrons



X-rays







- Neutrons can penetrate metals while still strongly interacting with light elements
  - Heavily attenuated by certain light elements such as ^{1}H, therefore highly sensitive to hydrogenous matter: water/hydrocarbons/fuel/plastics
  - High penetration in common engineering metals
- Highly complementary to X-rays
  - Nuclear (point) vs. electromagnetic (cloud) interaction
  - Elemental/isotopic composition vs. index of refraction

Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

Neutron Penetration depth : R. Pynn, "Neutron scattering: a primer." *Los Alamos Science* 19 (1990): 1-31. APS X-ray penetration depth: C. Powell, personal communication.

Approach

Approach is similar to ongoing work with GDI injectors (Neutron Imaging of Advanced Transportation Technologies)

Neutron Computed Tomography (CT)

High-penetrating and non-destructive technique for obtaining finely resolved geometric information (50-100 μm) over a large field of view (7 x 7 cm)

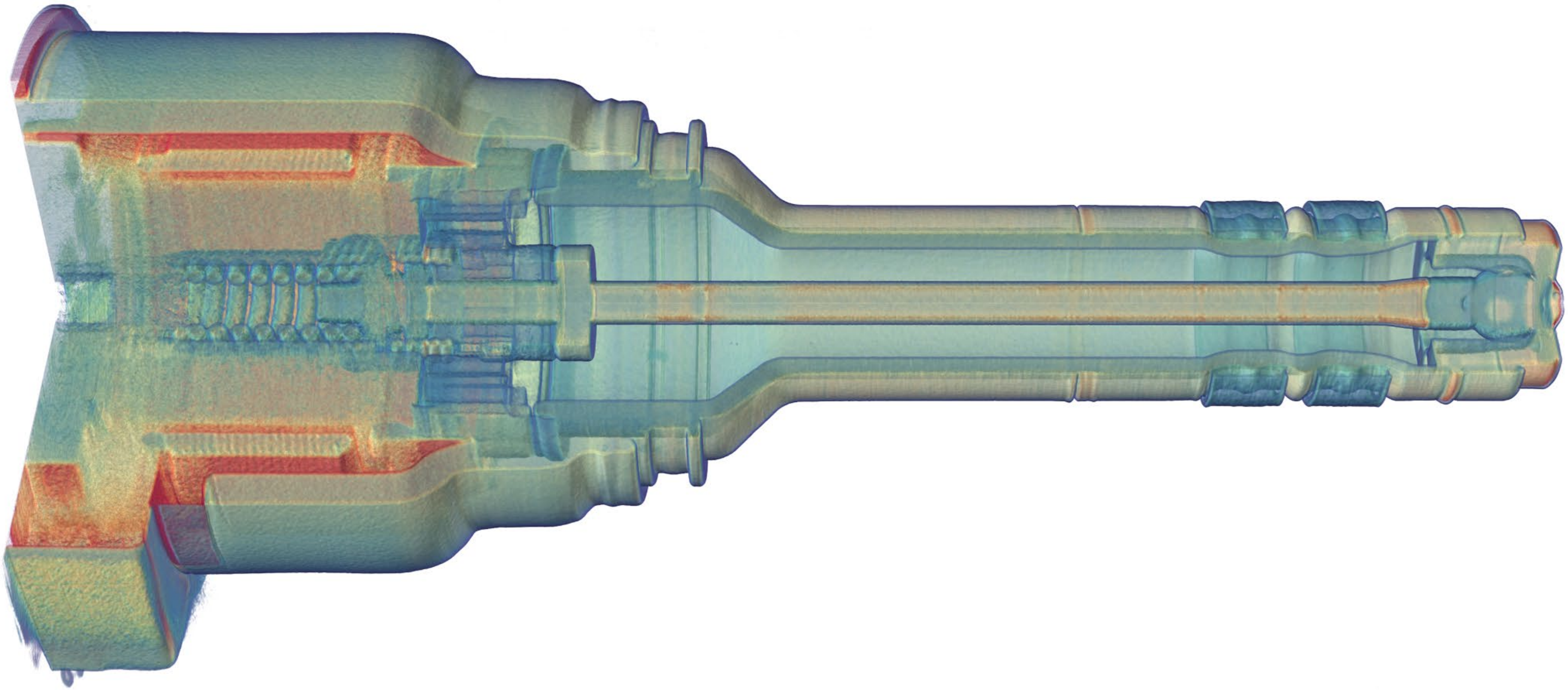
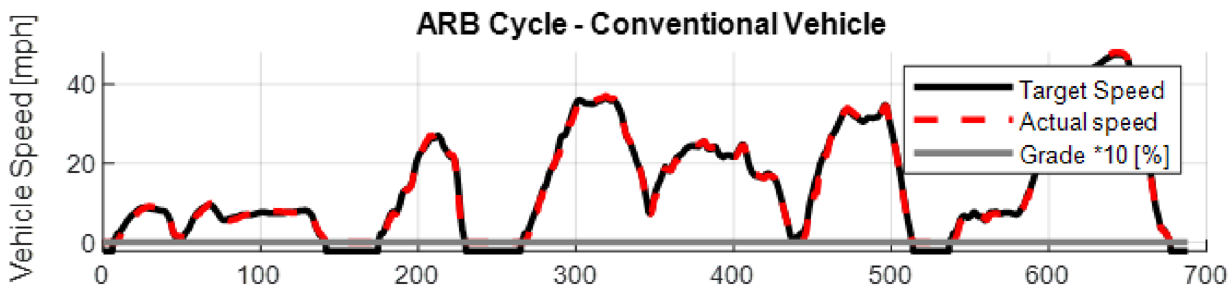
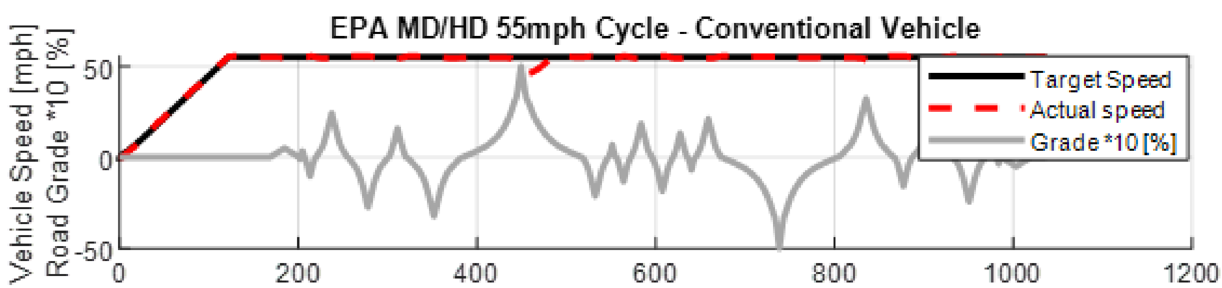


Image from previous DOE work on GDI injector

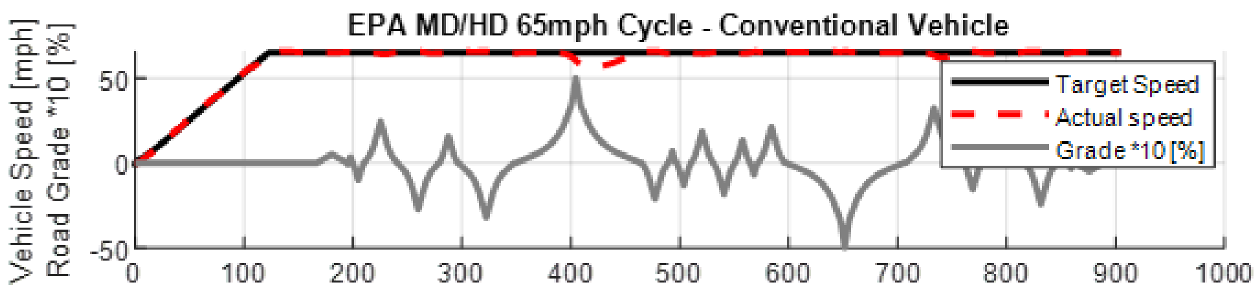
Drive cycles used: characterize hybrid architectures and engine combinations under investigation for heavy-load restarts

- ARB Cycle is low speed, with stops and starts, over flat grade
- Cruise cycles simply accelerate to speed (55, 65 mph), then maintain speed over different road grades





Constant speed Varying Grade



Constant speed Varying Grade

Collaborations & Coordination (Task 1: Combustion CRADA)

- **Cummins -** Project Partner, Tim Lutz(Co-PI)

Teamwork & Roles		
Cummins	**Joint**	**ORNL**
• Specifications • Modeling • Engine Cell	• Planning • Results interpretation • Joint Campaigns	• Diagnostics • Measurements • Data analysis

- **Joint measurement campaign at Cummins Technical Center**
  - Measurements of cylinder scavenging to improve design models
  - February 5th to March 1st, 2019
- **Cummins SuperTruck-II Project** – Diagnostic applications, J. Dickson (Co-PI)
- **Univ. of Central Florida** – Applied diagnostics, S.S. Vasu
- **Interactions with technical community**
  - 6 archival publication since CRADA last reviewed in 2016
    - J. Yoo, et al. (2016). Applied Spectroscopy 70, No. 4, 572-584.
    - K. Thurmond, et al. (2016). Applied Spectroscopy 70, No. 6, 962-971.
    - G. Jatana, et al. (2017). "Sensors and Actuators B: Chemical 240, 1197–1204
    - Z.E. Loparo, et al. (2017). "Combustion and Flame, 185, 220-233.
    - A.C. Terracciano, et al. (2018). New Space, 6, 28-36. ***Cover Feature***
    - G. Jatana, et al. (2018). International Journal of Engine Research, 19, No.5, 542-552.

ORNL Vehicle Systems Integration (VSI) - Laboratory

Shared Resources

- An **AVL 400 kW energy storage system** emulation with flexibility to simulate different energy storage systems as part of **"X"-in-the-loop** evaluations or when batteries are still in development
- A dSPACE **hardware-in-the-loop (HIL) real-time** platform for **vehicle system emulation**
- Engine-out and tailpipe **emissions measurement**

Powertrain Test Cell

- Uniquely capable of analyzing **light-duty** to full **heavy-duty Class 8** powertrains
- Configurations available to evaluate and characterize **engines, electric machines, transmissions,** and **integrated powertrains**

Component Test Cell

- Component "X"-in-the-loop environment including **engines, electric machines**, and **energy storage systems**
- **Light-duty focused** with medium-duty powertrain component capability

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